Review

Microwave Processing of Materials: Part II

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Abstract: The fundamentals of microwaves and fixed frequency microwave processing of materials, together with the successful applications of the technology in the United States of America (USA) and Australia, have been described in detail in the paper titled microwave processing of materials: part I. This paper, part II, describes and comments on the fundamentals of variable frequency microwave (VFM) facilities together with their successful applications in the USA, United Kingdom and Australia.

1. Introduction

In part I of the paper, many successful applications of microwave irradiation were elaborated. Microwave-based processing approaches can be broadly divided into either single-mode or multimode cavities. The single mode cavity approach makes use of a tunable microwave capacity specifically designed to support a single resonant mode at the frequency of the microwave source. This ensures maximum coupling of the microwave energy with the load. However, the single mode nature of the cavity limits the area of high electric field intensity and, thus, the size, shape and positioning of the material to be processed. The multimode cavity approach makes use of a cavity that is "overmoded", which means it is large enough to support a number of high-order modes, at the same frequency. However, the power distribution at a single frequency is uneven and can result in multiple hot spots (Lauf et al, 1993).

On account of the limitations of fixed frequency microwave sources and new discoveries, Kashyap and Wyslouzil (1977) showed that sweeping the frequency of a voltage tunable magnetron over 2450 ± 25 MHz produced better or comparable heating uniformity to that obtained by using the oven's stirrer. Mackay et al. (1979) first conceptualised the idea of the variable frequency microwave (VFM) facility and Bible et al. (1992) designed and built the first VFM processing system using a high power travelling wave tube (TWT) amplifier capable of supplying up to 2.5 kW power over the frequency range of 4-8 GHz. The frequency range can be extended by the addition of other TWTs. Variable frequency microwave energy is considered to be able to overcome the inherent problems found in attempts to apply conventional fixed frequency microwave irradiation to advanced materials processing applications (Lamda Technologies, 1998; undated). The new development of VFM offers a unique capability in providing uniform and rapid heating over a large volume with high-energy efficiency. This is achieved with variable multi-frequency microwave processing which opens the way for improvements by selecting the best frequency range for the material and process parameters (Taube, 2000).

2. Variable Frequency Microwaves (VFM)

In conventional microwave processing, microwave energy is launched at a fixed frequency of either 915 MHz or 2.45 GHz or 5.8 GHz or 24.125 GHz into a waveguide or cavity bringing with it inherent heating uniformity problems, like hot spots and thermal runaway (Thuery, 1992; Liu et al, 1996). Variable frequency microwave (VFM) technology is a new technique for microwave processing introduced to solve the problems brought about by fixed frequency microwave processing. The technique has been applied to advanced materials processing and chemical synthesis. It offers rapid, uniform and selective heating over a large volume and at a high energy coupling efficiency. This is accomplished using preselected bandwidth sweeping around a central frequency employing by tunable sources such as travelling wave tubes as the microwave power amplifier. Selective heating of complex samples and industrial scale-up are now viable (Liu et al, 1996; Wei et al, 1998). At the heart of the VFM technology is a high power, broadband, helix travelling wave tube (TWT), which has been used in the VFM facilities constructed to date (Everleigh et al, 1994).

When microwave energy of a fixed frequency, eg 2.45 GHz is launched into a waveguide eg WR229, as depicted in figure 1(a), containing a piece of material, some areas of the material would experience higher electric field strength than others. This situation is even more profound if the microwave energy is launched into a multimode cavity because many resonant modes can be established. Figure 1(b) shows the fixed electric field pattern across any cross section of the joint of the test pieces during fixed frequency heating. Those areas with higher electric field strength would be heated more, creating hot spots, which could even lead to thermal runaway. With variable frequency microwave heating, as shown in figure 2(a), more than one thousand frequencies are launched into the cavity sequentially (Wei et al, 1998). At each incident frequency a unique electric field pattern is set up across any cross section of the joint of the test pieces, which results in hot spots at different locations at different times, as shown in figure 2 (b). Different areas are thus heated under different frequencies and at different times. When a sufficient bandwidth is used, every element of the test piece experiences hot spots at one or more frequencies during sweeping. Therefore, time-averaged uniform heating is achieved with proper adjustment of the frequency sweep rate and sweep range. Another advantage of the VFM heating is the capability of providing precise frequency tuning to optimise the coupling efficiency. In summary, the characteristics of VFM heating include:

- Selective frequency control

- High energy coupling efficiency
- Scaleable to large processing volume
- Uniform heating throughout

The two VFM facilities currently available in a university in Victoria, Australia are Microcure VW 1500 (Figure 3) and Microcure 2100 Model 250 (Figure 4). The Microcure VW1500 has a maximum power output of 125 W and generates microwave energy in the frequency range of 6.5 – 18 GHz. The Microcure 2100 model 250 operates at 2 - 8 GHz with a maximum power level of 250 W. The cavity dimension of Microcure VW1500 are 250 mm x 250 mm x 300 mm and the Microcure 2100 model 250 has a cavity size of 300 mm x 275 mm x 375 mm. The curing cavity used in the VFM facility is a square metal enclosure where microwave processing or curing process takes place. The cavity features a manual hinged door with microwave seals around the perimeter of the facing door. The door seals provide good electrical contact and prevent microwave leakage from the cavity enclosure. In the cavity, four pass through ports for fibre optic temperature probes are incorporated together with a choke and view port for the infrared temperature sensor when this option is selected. The samples being processed are placed directly on a suitable microwave transparent fixture such as a Teflon block or solid PTFE cylinder. They are therefore off the cavity floor at a minimum distance of 20 mm (Lambda Technologies Inc., 1998; Bow, 1999). The Teflon block has to be used in all experiments to avoid consequences of heating a product directly in contact with a metal surface, since there will be a minimum electric field condition at the contact of the material with the metal base of the cavity.

The Microcure VW1500 and 2100 model 250 both consist of several separate subsystems. The subsystems (Lambda Technologies Inc, 1998) comprise curing cavity, oven control system, signal generator and high power amplifier (HPA) system, transmission system, and fibre optic base temperature monitoring system. A block diagram showing the Microcure 2100 sub-systems is shown in Figure 5.

There are four adjustable processing parameters that distinguish the VFM facility from conventional, single frequency microwave based technologies. These controllable processing parameters include central frequency, bandwidth, sweep rate and power. During processing, the central frequency irradiated inside the microwave cavity can be tuned to increase the coupling efficiency with the material to be processed. In materials with frequency sensitive dielectric behaviour, the central frequency can be adjusted to increase the dielectric loss of the material. Thus, the heating rate can be increased without changing the power. The combination of bandwidth and sweep rate around the selected central frequency, utilised during processing, provides the necessary distribution of microwave energy to carry out uniform heating throughout the workload. The sweep rate can be varied from milliseconds to minutes. The microwave power can be continuously varied or pulsed to provide some control over the heating profile of the workload (Zathi et al, 1995).

3. Applications of VFM in the USA

Demeuse and Johnson (1994) reported that they have successfully heated up and post-cured large (>100 cm^2) plates of thermoset polymer matrix composite (PMC) material consisting of isocyanate/epoxy mixtures. Previous work has indicated that microwave energy is capable of reducing the time or the temperature necessary to achieve full cure (Ku et al, 1997a: 1997b). However, single frequency microwave processing results in non-uniformity of heating/curing in areas of over 12.5 cm^2. By using a VFM facility and the sweeping frequency range of 5-6 GHz at a power level of 150 W, uniform heating and curing of the PMC plates was achieved over an area of over 100 cm^2 and over a volume of 200 cm^3. The overall temperature gradient across the surface of the plate was found to be less than 10%. It was also found that there were definite effects of sample size on the observed microwave heating features, especially the volume-to-surface-area ratio increased heating to a desired isothermal temperature. This has been attributed to heat loss from the surface of the sample.

Fathi et al. (1995) reported on the post-curing characteristics of several isocyanate-based polymeric matrix composite (PMC) plates. The isocyanate/epoxy systems have a rather short cure-cycle of 3 minutes and a very long post-cure cycle of 8 hours at a temperature of up to 240^{o}C when cured in conventional furnaces. Using the VFM facility, several experiments were carried out using different sample arrangements. All plate-shaped samples were 100 x 100 x 25 mm. The temperature across the samples was measured using a four-channel fibre-optic temperature monitoring system. Heating of a series of plate configurations was performed with 1, 2, 3, 4 and 8 plate stacking. The glass transition (T_g) values of a three plate stacking configuration processed at 175 ^{o}C for 60 minutes using 4-5 GHz at 150 W were measured at different locations, and the results were 168 ^{o}C, 172 ^{o}C and 165 ^{o}C. When eight plates were stacked and uniformly processed at 200 ^{o}C for 60 minutes, the glass transition temperature was measured at five locations and the results were 193 ^{o}C, 192 ^{o}C, 201 ^{o}C, 206 ^{o}C and 190 ^{o}C respectively. The measured glass transition temperatures were close to the cure-soak-temperature. All samples were cured uniformly and warpage was not observed. By employing VFM technologies, it was found that not only the processing time had been reduced from 8 hours to 1 hour, the temperature used in the curing process had been also lowered from 240 ^{o}C to 200 ^{o}C. Therefore time and energy was saved.

Wei et al. (1996) employed a variable frequency microwave (VFM) furnace to characterise and diagnose materials for quality control and evaluation. Though various microwave-assisted non-destructive evaluation (MA-NDE) systems have been developed for materials inspection, none of them can be applied to materials within a mould or reactor. A broadband variable frequency microwave based resonant mode MA-NDE was studied as an alternative for the characterisation of materials within a cavity. The main advantage of the resonant mode MA-NDE is non-intrusive and volumetric diagnosis of the material inside a mould. The resonant mode MA-NDE technique is based on a VFM concept and interactions between microwaves and materials. When a microwave signal of a given frequency is launched into a metallic cavity which is fully or partially filled with materials, microwaves will reflect back and forth between cavity walls and travel through the material many times before establishing a final standing wave condition. As a result of all these wave reflections and attenuations, the microwave signal may be: i) totally confined within the cavity, ii) totally reflected back to the launcher, or iii) partially confined and partially reflected. The final condition depends on the microwave frequency, cavity dimensions, and material properties. Materials properties include the physical geometry, dielectric properties, internal or surfaced defects, and chemical and physical properties. The ratio between the reflected signal and the input signal can be monitored and plotted as a function of the frequency. This signal ratio versus frequency is called the microwave reflectance spectrum. For given frequency range and cavity dimension, dimensions of the material and the location of the material inside the cavity, the spectrum is purely a function of the nature of the material. Therefore this spectrum can be used as a signature curve for the product quality during processing. In other words, products of high quality will share a common characteristic curve, which is different from that of lesser quality products.

Zathi et al. (1998) used VFM energy to uniformly cure glass reinforced isocyanate/epoxy mixtures as well as graphite fibre reinforced epoxy. Several samples were heat treated using high heating rates under an average microwave incident power of 280 W. The samples heat treated under these conditions were fully cured in 50 minutes. The glass transition temperature is plotted as a function of curing temperature. Full curing is achieved for curing temperature above 230 ^{o}C. The dielectric constant and dielectric loss were found to increase with increasing temperatures, followed with a decrease past the 170-180 ^{o}C temperature range. A change in storage capacity of the material is generally correlated to structural changes occurring at molecular level. The structural changes occurring at the 170-180 ^{o}C temperature range can be reasonably correlated to the onset of further curing and the formation of a 3-D network. Thus, the dielectric property measurements might be a good indication of the on-set of post-curing. This interpretation is further supported by the results of the measured glass transition temperatures, T_g, which have values comparable to curing temperature when the samples are heat treated below 180 ^{o}C. While those measured for samples heat treated above 180 ^{o}C are different.

Wei et al. (1998) presented two successful bonding applications: i) bonding of polymers composites, including urethane-based SRIM (structure reaction injection moulding) glass fibre composite panels and fibre glass reinforced polyester panels, for automotive applications, and ii) curing of encapsulant in Direct Chip Attachment (DCA) for electronic packaging applications. The study showed that VFM has the ability to provide selective, yet uniform, heating of adhesives even for a large sample size relative to the cavity. Sufficient bonding strength was achieved with reduced cycle times in both cases. The selective nature of VFM bonding also offered advantages, such as reducing residual stress as in the bonded products.

The demand for smaller, lighter, faster and cheaper products has placed tremendous requirements on semiconductor manufacturers. These demands force manufacturers to develop new packaging assembly techniques. The solution for the problems is to incorporate DCA or flip-chip, ie attaching a bare silicon die directly to a circuit card as opposed to packaging the device and then mounting it onto the circuit card. In the process, advanced adhesives and encapsulants are required to attach and protect these devices. Anderson et al. (1998) and Fathi et al. (1998) used VFM facilities to cure the adhesives and encapsulants successfully in much shorter time intervals than using the conventional ovens. The curing time of the flip-chip underfill was reduced from 30 to 60 minutes to around 5 minutes. Zou et al. (1999) studied and compared the die level stresses in chip-on-board (COB) packages processed with convention and VFM encapsulant curing. Using special orientation silicon stress test chips, the die surface stress due to encapsulation was measured for a commercial liquid encapsulant material processed with both convection and VFM curing. The test die had dimensions of 10.2 mm x 10.2 mm and contained an array of optimised eight-element dual polarity piezoresistive sensor rosettes that were uniquely capable of evaluating the complete stress state at points on the surface of the die. A comparison was made between room temperature stresses found with each method of curing. After cure, the samples from each curing method were divided into two groups, and reliability tests were performed. Overall, VFM curing was found to offer similar stress levels and reliability, reduction in substrate warpage, and greatly reduced cure times when compared to conventional curing.

Tan et al. (1998) has fired four types of bauxite materials, namely: raw bauxite, beneficiated bauxite, tailing pond material and capping material using a variable frequency microwave oven. The cylindrical extrudates used in the tests had dimensions of ∅12 mm x 30 mm. The mullite, corundum and cristobalite phases, which developed in the fired extrudates, were quantitatively determined by X-ray diffractrometry and it was revealed that the extrudates contained gibbsite, kaolinite, and small amounts of anatase, rutile and quartz. The results obtained from this investigation have indicated that at 1350 ^{o}C, the weight loss of extrudates fired conventionally was similar to that obtained in the microwave furnace. However, less volume contraction occurred in extrudates fired in the microwave furnace as compared to conventionally fired extrudates. There was no significant difference in the amount of corundum and mullite that developed in extrudates fired in each type of furnace, provided that sufficient soaking time was allowed. At 1100 ^{o}C, gibbsite completely converted to corundum in just 1 minute in the microwave furnace. No significant difference in physical properties was detected in extrudates fired at the same temperature of 1350 ^{o}C for 30 minutes in the microwave oven, as compared with 1 hour in the conventional furnace. The electrical power requirement for firing the extrudates in the microwave furnace during the ramp and soak periods was 1.2 and 0.8 kW respectively, while those for conventional oven were 5.0 and 2.0 kW respectively. The times required for microwave processing during the ramp and soak periods were 20 minutes and 30 minutes respectively, while those for conventional furnace were 270 and 60 minutes respectively. The total energy required for the microwave system was $1.2kWx\frac{20}{60}h + 0.8kWx\frac{30}{60}h = 0.8kWh$, while that needed for the conventional oven was $5.0kWx\frac{270}{60}h + 2.0kWx\frac{60}{60}h = 24.5kWh$. By using the VFM oven, savings in energy requirement are of the order of 96.7 %, and in processing time of the order of 85%.

Lambda Technologies (2000) introduced the VFM curing technology to the automotive industry with the cooperation of Loctite Corporation, which used VFM in its FastGasket® sealing and assembly systems. Loctite's FastGasket® sealing systems dispense high-volume, cured-in-place silicone gaskets for a wide range of automotive assembly applications. VFM enables the gaskets to be cured up to 10 times faster than with traditional convection ovens. Also, by selectively heating the gasket being cured, while allowing the surrounding assembly to remain much cooler, VFM allows parts to be handled and packaged immediately after curing, thus greatly increasing throughput. In addition, VFM ovens occupy 30-40% less floor space than convection ovens, generate negligible ambient heat and consume virtually no energy while idling, resulting in significant savings in air conditioning and energy costs as well as factory floor space.

4. Applications of VFM in United Kingdom

In United Kingdom, the application of variable frequency microwave (VFM) facilities worth mentioning is in foodstuff processing. Bows and Mullin (1994) proposed that batter used to coat frozen substrates such as fish could be processed by the use of high frequency heating above 3 GHz. The penetration depth of commonly used batter (58% water, 20% wheat flour, 20% starch and 2% salt) at 2.45 GHz and 7 GHz and at 10^{o}C and 70^{o}C are tabulated in Table 1. 10 ^{o}C and 70 ^{o}C are the enrobing temperature and the minimum temperature required to set the batter at 2.45 GHz and 7 GHz respectively. Assuming an enrobing thickness of 2 mm and at the enrobing temperature, a microwave signal at 7 GHz would be concentrated in the coating, compared with heating at 2.45 GHz, as the penetration depths (at 10^{o}C) are 1.5 mm and 3.5 mm respectively. A conventional fixed frequency (2.45 GHz) microwave oven cannot enrobe and set the coating only as the penetration depths are 3.5 mm and 2.8 mm respectively at 10^{o}C and 70^{o}C. On the other hand, the recently commercially available variable frequency microwave (VFM) heating facilities can perform the tasks with ease (Bows, 1994).

Clark and Holt (1989) describe the way to heat the interior of an ice cream dessert, melting a chocolate core whilst the outer ice cream remains frozen. To achieve this with a fixed frequency (2.45 GHz) a microwave oven would require manufacture of the product to within millimetre precision, which is not realistic with commercial manufacturing practices. Using VFM ovens, Bows (1999) claims that it is possible to control the microwave heating by selecting the appropriate frequency.

5. Applications of VFM in Australia

Siu et al. (1999) carried out non-destructive testing and evaluation on adhesively bonded polycarbonate specimens using VFM. The dimensions of the polymer samples were 101 x 25.4 x 1 mm and the lapped area was 6.45 cm^2. A flexible general-purpose epoxy adhesive was utilised, which was conventionally cured at 65 ^oC isothermally for 40 minutes. By comparing a microwave reflective spectrum during the production processes to standard spectra, a computerised monitored system regulated the process-input parameters for proper adjustment and compensation. The evaluation system provided an on-line monitoring feature. Such methodology can be used for assessing and evaluating product quality.

Ku et al. (2000a) characterised five different thermoplastic matrix composite materials using two VFM facilities, Microcure VW 1500 and Microcure 2100 model 250, to find out the best frequency range to process the materials by microwave irradiation. The five thermoplastic matrix composite materials were 33 percent by weight (33 wt-%) random carbon fibre (CF) reinforced polystyrene [PS/CF (33%)], 33 wt-% random CF reinforced low density polyethylene [LDPE/CF (33%)], 33 wt-% random glass fibre reinforced polystyrene [PS/GF (33%)], 33 wt-% random glass fibre reinforced low density polyethylene [LDPE/GF (33%)] and 33 wt-% random glass fibre reinforced Nylon 66 [Nylon 66/GF (33%)]. Microcure VW 1500 characterised the materials between 6.5-18 GHz, while Microcure 2100 model 250 processed the materials in the frequency range of 2-8 GHz. Using LDPE/GF (33%) as an example, the ratio of the incident power to the reflected power, ie the percentage of reflectance, in the characterisation of the material in the frequency range of 2-8 GHz, is plotted against the frequency and the result is shown in Figure 6. Similarly, the result of the characterisation in the frequency range of 6.5-18 GHz is depicted in Figure 7. By analysing Figures 6 and 7, it was found that the percentage of reflectance (20%) was lowest in the frequency range of 9.0-12.5 GHz. The best frequency range to process LDPE/GF (33%) using the VFM facility in the frequency range of 2-18 GHz was therefore from 9-12.5 GHz. The optimum frequency bands for processing the five thermoplastic matrix composites in the frequency range of 2-18 GHz are summarised in Table 2.

Ku et al. (2000b) joined two tensile test pieces of PS/CF (33%) and LDPE/CF (33%) with a lapped area of 200 mm^2 using the VFM facility. Neither the bond strength of PS/CF (33%) processed at variable frequency, nor that of LDPE/CF (33%) processed at fixed frequency in VFM facility seemed to reach the strengths of their parent materials respectively. Hot spots were found on the joint of LDPE/CF (33%) joined using the fixed frequency of 2.5 GHz chosen from the VFM facility. However, the joint of PS/CF (33%) processed by variable frequency was perfect. It could therefore be argued that VFM could produce stronger bonds for the two materials, PS and LDPE, with excellent quality of joint properties. It was found that with carbon fibre reinforced thermoplastic materials, fixed frequency joining could not be pursued since the carbon fibre would arc and this can give rise to thermal runaway thus resulting in deformed or even burnt samples. It was also found that the power level was vital in joining thermoplastic composites irrespective of whether fixed or variable frequency microwave irradiation was used, and that for LDPE/GF (33%) the bond strength does not improve much with increasing the duration of microwave irradiation, irrespective of whether fixed or variable frequency microwave energy was employed.

Siores et al. (2000) joined LDPE/GF (33%) using VFM with rapid araldite as primer and it was found that the bond strength was only 21.5% more than that cured in ambient conditions. The processing time taken to cure the adhesive was relatively long (180 – 420 seconds) as compared to that cured by the focused fixed frequency microwave facility. The above drawbacks were entirely due to the low maximum power output of the VFM facility. This can be overcome by employing a larger power facility, eg the 2kW power of Microcure 2100 model 2000. Nevertheless, the overall quality of bonds produced by VFM processing has been much superior to those produced using its fixed frequency counterpart.

Ku et al. (2000c) characterised two adhesives commonly used in encapsulation. One of the adhesives is the Uniset adhesive A- 312-20 made by Amicon and the best frequency to process it by VFM oven is in the frequency range of 10-12 GHz. The other is Hysol encapsulant EEO-1060 was made by Dexter and it was best processed at 10-12 GHz. The percentage of reflectance of Uniset adhesive in the frequency range mentioned was 20% and that of Hysol encapsulant was 25%. This meant that the Uniset adhesive was coupled better and hence absorbed more microwave energy in the frequency range mentioned. With these results on hand, the adhesives can be used to coat the die attached by Direct Chip Attachment (DCA) in the printed circuit board assembly (PCBA) and cured in the VFM facilities with optimum parameters, including processing between 10-12 GHz. Non-Destructive Evaluation using VFM can also be carried out simultaneously to control the quality of the product on-line.

6. Conclusion

The concept, development, operating principles, input-parameters, merits and limitations of the variable frequency microwave furnace have been explained in detail. Successful applications in the United State of America, United Kingdom and Australia have also been described. Another thing that is worth mentioning in the characterisation of materials is that whether it is absolutely correct to relate the power reflectance of the microwave cavity to the dielectric properties of the materials. The reason for this is that at any particular frequency, a number of different modes, each having a different field pattern, can be excited within the cavity. The extent to which each one of these is excited depends on the coupling of the source to each mode, and is not susceptible to measurement. Therefore the electric field pattern within the cavity is extremely complex and unpredictable (Ku, 2000a). Faced with such a complex situation, the best way to proceed is on a semi-empirical basis. In this paper, most of the successful applications of variable frequency microwave (VFM) processing of materials are in the areas of curing polymer or polymer-based composite materials used in semiconductor industries. However, one application in the area of firing bauxite materials and another in quality assurance and control, using microwave reflective spectrum in the United Sates of America are described. Moreover, two applications of foodstuff processing in United Kingdom are also mentioned. Because of the high cost of the variable frequency microwave (VFM) facilities, at this point in time, material processors will invest only in those facilities, if the items processed have high value, eg electronic and computer components. Finally, to reduce the time consuming experimental empiricism that is required to develop relatively simple heating procedures, computer simulations of fixed and variable frequency heating may be employed (Bows, 1999; Dibben and

Metaxas, 1994) and this will be described in detail in part III of the paper together with the cost and benefit analysis of microwave processing.

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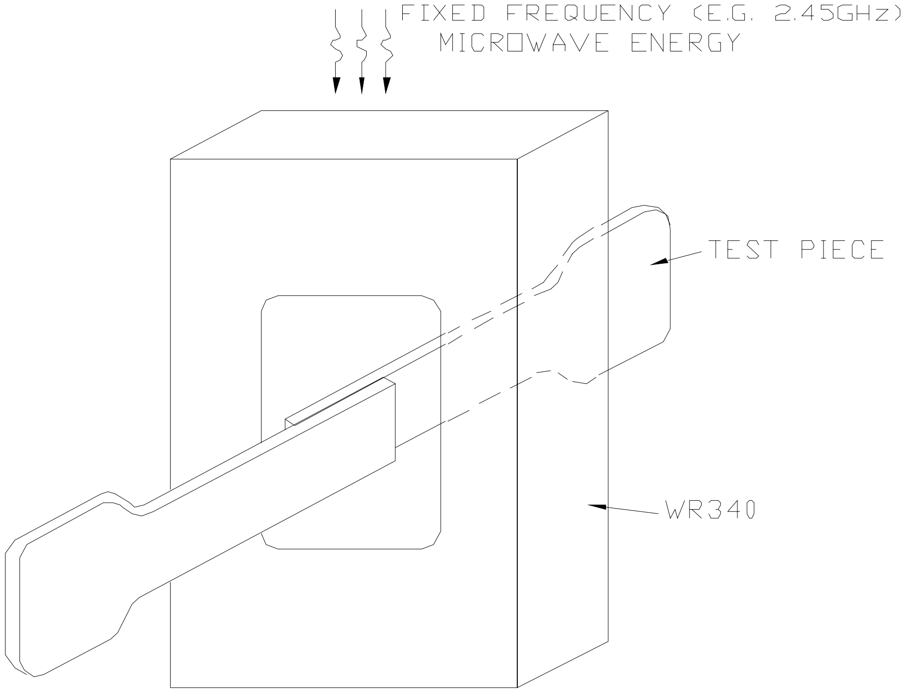
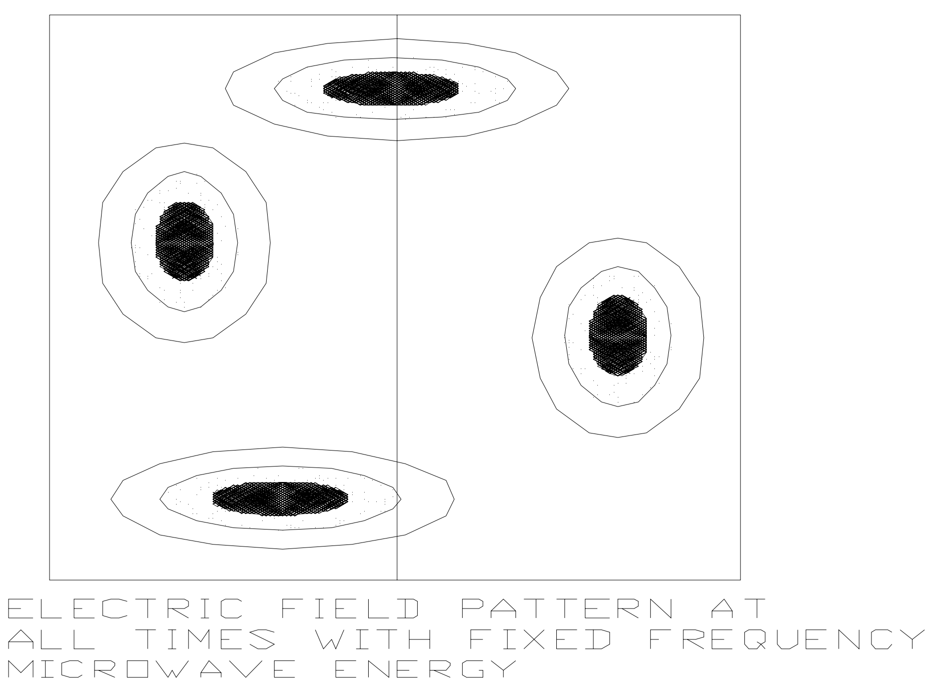
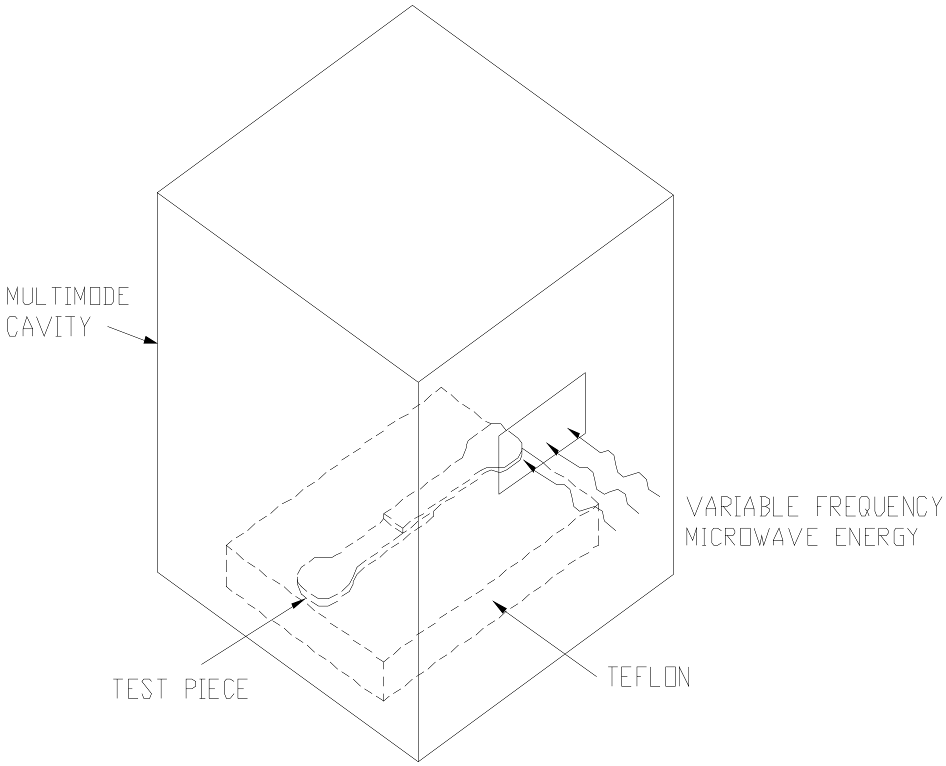


a) 2.45 GHz Microwave Energy launched into a Single Mode Applicator

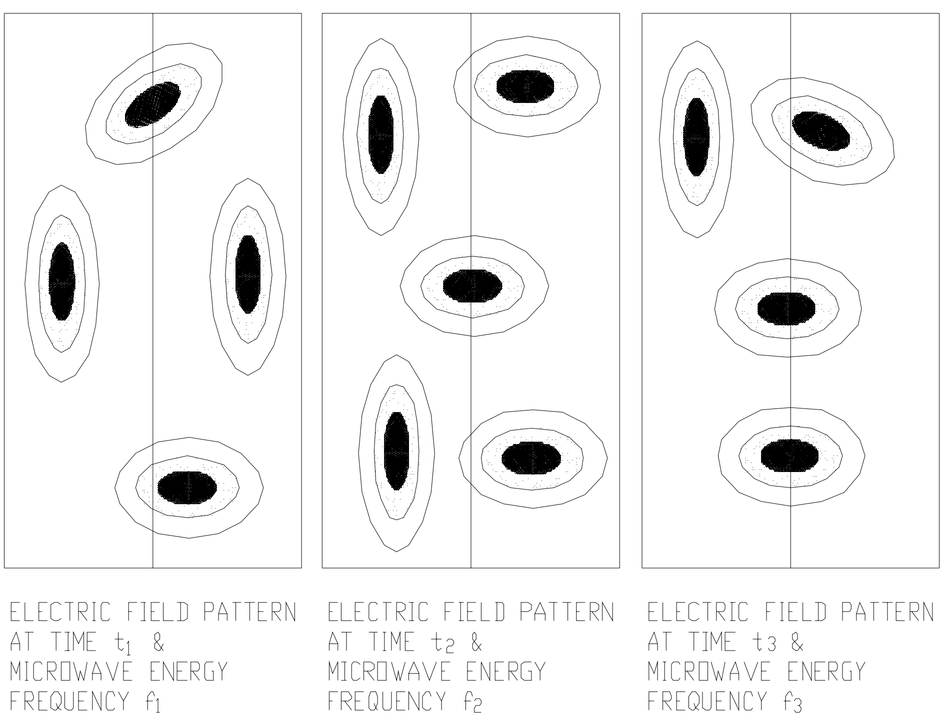


b) Electric Field pattern for (a)

Figure 1: Fixed Frequency Microwave Heating – Nonuniform Heating



a) Variable Frequency Microwave Energy launched into Multi Mode Cavity



b) Electric Field pattern at Different Times in (a)

Figure 2: Variable Frequency Microwave Heating – Time-Averaged Uniform Heating

Figure 3: The Cavity of Microcure VW1500

Figure 4: The Cavity of Microcure 2100 Model 250

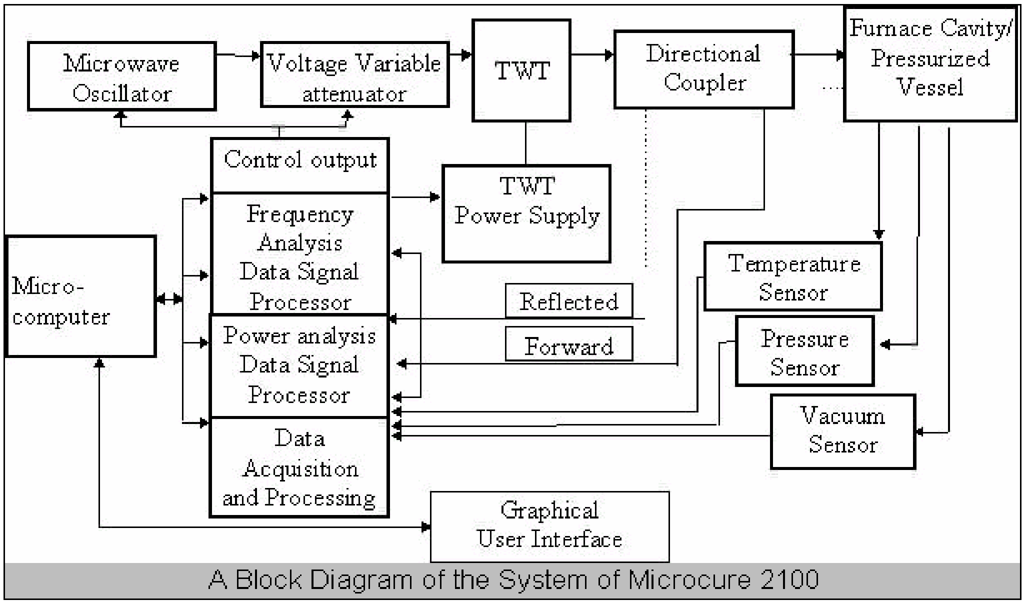


Figure 5: A Block Diagram of the System of Microcure 2100

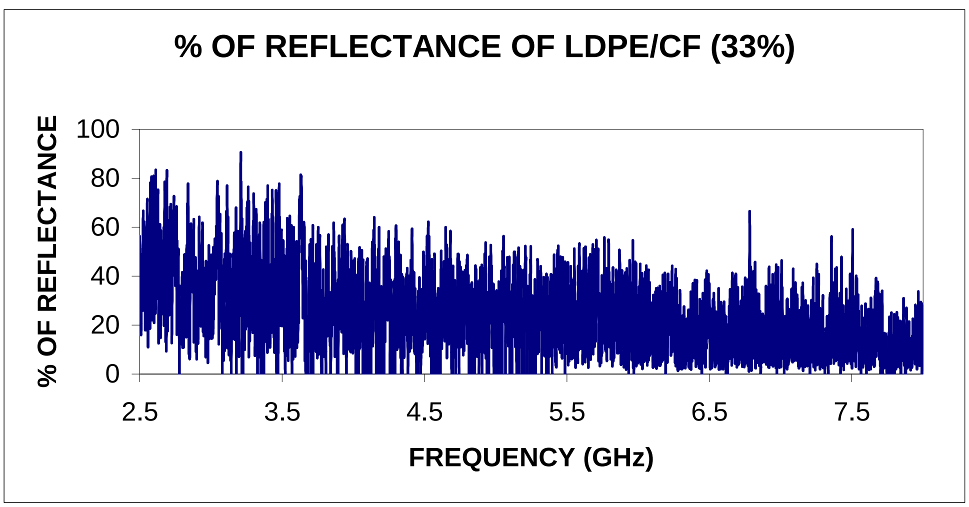


Figure 6: Percentage Reflectance against Frequency for LDPE/GF (33%)

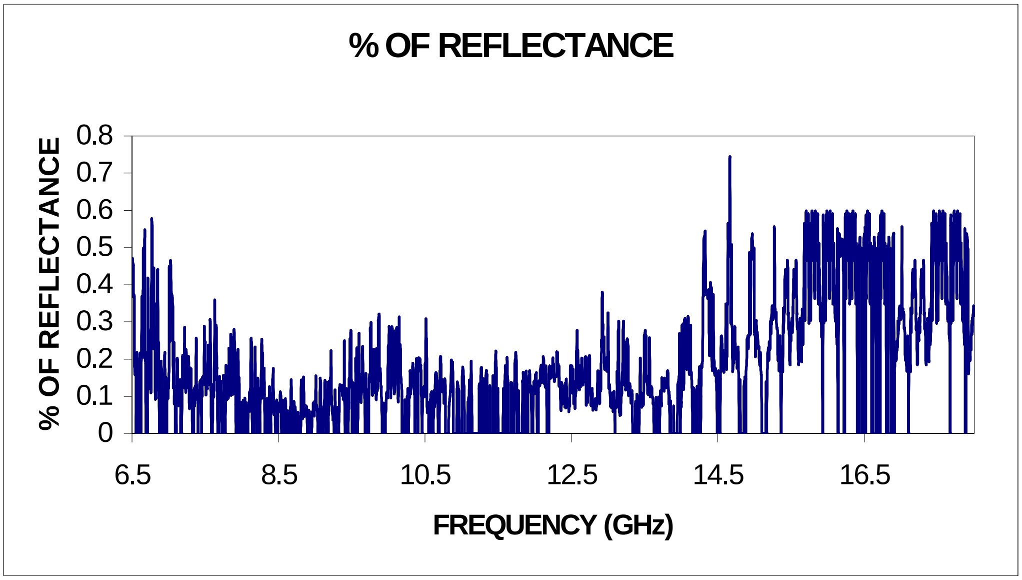


Figure 7: Percentage Reflectance against Frequency for LDPE/GF (33%)

Table 1: Penetration Depths of a Commonly used Batter at Different Temperatures and Various Frequency

	Frequency:	2.45 GHz	7 GHz
	Temperature		
Penetration depth (mm)	10°C	3.5	1.5
	70°C	2.8	1.7

Table 2: Optimum Frequency Bands to Process the 5 Materials in the Frequency Range of 2 GHz to 18 GHz.

Materials	Optimum Frequency Band (GHz)
PS/CF(33%)	8.0 - 9.3 and 10.8 - 12.8
PS/GF(33%)	8.5 - 9.0 and 10.0 - 12.0
LDPE/GF(33%)	9.0 - 12.5
Nylon 66/GF(33%)	8.3 - 9.0 and 10.8 - 12.0
LDPE/CF(33%)	8.5 - 9.0 and 10.7 - 12.0